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THE MICROSTRUCTURE OF CLOUDS

STAT

Ye. S. Selezneva

/Figures are appended./

Among the broad problems of cloud physics and precipitation, perhaps the most neglected are those on microphysics. For the past 10-15 years, our information has been supplemented by the used of aviation in the study of atmospheric processes and by the development of laboratory experiments. Despite this, however, factual data is completely lacking and no methods have been devised for obtaining it on some elements of cloud microphysics (e.g., data on the size of condensation nuclei, the electric charge of drops, etc.); on other elements such as the amount of water and number of particles only approximate values have been obtained.

In this paper, only a few of the microphysical properties of clouds -- drop size, amount of water in clouds, and number of drops per unit volume -- can be considered.

The most definite and reliable data is that on the microstructure of cloud droplets; the average size was repeatedly determined by diffraction rings and later distribution curves were obtained with the help of microscopic measurements.

The first measurements of cloud elements in the Soviet Union were made in the Gagry expeditions of the Leningrad Institute of Experimental Meteorology in 1935 - 1937 ("Problems of Experimental Meteorology," Trudy NIU GUGMS SSSR, Series I, No 1, 1941). In 1939, some observations were organized on cloud microstructure in the El'brus expedition of the Academy of Sciences USSR (by groups of the Leningrad Institute of Experimental Meteorology and Leningrad State University) at altitudes of 3,000 to 4,250 meters. In these works, detailed observations were made of the type of cloudiness at the lower points as it was important to relate the structural

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characteristics to cloud types. The same set of microphysical observations was repeated in 1940, and it was suggested that these studies be continued. In 1940 and 1941, measurements were begun on cloud drops from airplanes and balloons (Leningrad Institute of Experimental Meteorology and the Central Aerological Observatory). Therefore, the first results of the El'brus expedition in 1939 were considered preliminary and were given only in a short paper published recently (Ye. S. Selezneva, "Cloud Structure According to Observations Made in the El'brus Expedition of 1939," Trudy NIU GUGMS SSSR, Series 1, No 7, 1946).

Meanwhile data on measurements made in other countries has appeared. In 1939, studies of clouds were organized in France at the peak of Puy-de-Dome; the cloud type was determined at a station at the foot of the mountain (I. Bricard, "Study of the Constitution of Clouds at the Summit of Puy-de-Dome," La Meteor., Mar/Apr 1939). After the war, we became acquainted with the results of special flights in different clouds over Germany in 1940-41 (M. Diem, "Measurement of the Size of Cloud Elements, Ann. d. Hydr., 1942).

The main characteristics which we obtained on El'brus were confirmed, but it is now useful to reconsider and supplement them with the data of the above studies.

The method of microphotography of sample drops taken from clouds on an object glass covered with a fine oil film was used on El'brus. The characteristics and variations of this method have been described repeatedly and will not be considered in this article. We point out only that there are boundaries with respect to both large and small drops for the method of microphotography used at present. The lower boundary (for very small drops) is established by the resolving power of the microscope, the properties of the film, and the method of taking the drop samples from clouds. Ordinarily, drops of diameter 1-1.5 microns are the smallest drops which can be measured in microphotography. Large drops flatten out when they fall on the object glass and also deform rapidly because of coalescence, so that drops with diameters of 100 to 200 microns are measured inaccurately.

These last remarks should be kept in mind in evaluating the results of measurements and in constructing distribution curves of drops. We could assume that there are in clouds a great number of very small newly forming or already evaporating droplets, and then the form of the distribution curves might be different than that which is given below for accurate ultramicroscopic measurements, i.e., the maximum of the curve might lie in the region of drops up to one micron. Khvostikov found confirmation of this assumption in optical studies (I. A. Khovostikov, "Some Problems of the Optics of Fogs," Iz Ak Nauk SSSR, Ser Geograf i Geofiz, No 3, 1942). However, there is not complete confidence now in this theory of ultrasmall drops permanently persent in clouds, since such drops can exist according to thermodynamic considerations for only a short time as transitory phenomena; they rapidly grow larger under favorable conditions or else evaporate completely. Consequently, a great number of very small embryo drops can be assumed only for newly forming clouds.

Thus, we accept that cloud drops with diameters from 1 to 100 microns have now been reliably investigated, and we will discuss these drops. First, we will compare the results obtained at El'brus, on Puy-de-Dome, and in one other study (B. V. Kiryukhin, "Evaporation of Water Droplets and Water Solutions of Salts," Trudy NIU GUGMS SSSR, Series 1, No 1, 1946), as shown in Table 1.

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Table 1. Predominant Sizes of Drops in Clouds (diameter in microns)

Cloud	El'brus	Puy-de-Dome	Free Atmosphere Over Germany
St	5-10	8	6-9
Cu	7-10	11	7
Sc	--	15	9
Ns	15	20	22

We note that drops of diameter 5-10 microns predominate in St and Cu clouds, while somewhat larger drops are found in Cb and Ns. In other types of clouds (Cu cong, Sc, Ac) the drops are of somewhat intermediate sizes, but change considerably for different cases. The drop size may also fluctuate somewhat at different heights for the same cloud. Careful processing generally shows that the difference in average (or modal) drop sizes in different types of clouds can be revealed only by averaging many measurements. The distribution curves of drops are more descriptive.

We constructed distribution curves by the usual method according to frequencies of different sizes of drops. For some purposes (e.g., evaluating the water content of clouds and fogs), Houghton derived curves of relative volumes with coordinates diameter (or radius), and $v = \frac{d_i^3 n_i}{\Sigma d_i^3 n_i}$ relative volume, where n_i is the frequency; for other tasks (e.g., optical studies), it is useful to consider curves constructed for surfaces or cross-sectional areas ($S = kd^2n$). Some remarks will be made later on relative volume curves, but we now consider the ordinary distribution curves shown in Figures 1, 2, 3, and 4.

The majority of cloud types are characterized by simple distribution curves with one sharp maximum. Structrual differences appear in the kurtosis and skewness of the curves, e.g., sometimes these curves have low dispersion and are almost symmetric (Figure 1), while in other cases the maximum is smoothed out and the curve is sharply right-skewed (Figure 2). In addition to simple distribution curves, however, there are frequently the more complex, with two or several modal peaks (Figures 1 and 3). Houghton (H. G. Houghton and W. H. Radford, "On the Measurement of Drop Size and Liquid Water Content in Fogs and Clouds," Phys. Oceanogr. and Meteor., Mass. Inst. of Techn., Vol 6, No 4, 1938) feels that a regular curve having a unique maximum is always obtained when the number of particles measured is sufficient (at least 1,000). However, the El'brus observations and airplane data confirm the reality of multimodal curves, and only because the curves with one maximum predominate is this form retained for averaging and summing a number of cases, particularly when relating to different cloud types.

At first it was supposed that nonuniform drop sizes were created by the different types and sizes of condensation nuclei. Condensation covers nuclei gradually, at first the larger and more active and then the smaller and less active with respect to physicochemical properties the drops forming under these conditions should be of different sizes. This opinion was supported by such authorities on problems of atmospheric condensation as Kohler and Schmaus. Now we look at this problem from a slightly different standpoint. Simple calculations show that for the same atmospheric conditions, drops which are initially nonuniform will after a certain time become close in size, since the drop radius increases nonuniformly (the increase slows down with increasing r) in the condensation process.

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Let us use a formula which was obtained by a number of authors (Ye. S. Selezneva, "Condensation Nuclei in the Atmosphere," Trudy NIU GUGMS SSSR, Series 1, No 7, 1946; T. Bergeron, "Lectures on Clouds," Izd TsUEGMS, 1934):

$$r_2^2 = r_1^2 + a(E_r - E_\infty)t$$

where r_1 is the initial radius of the drop or condensation nuclei, r_2 is the drop radius after a time t seconds, E_r is the water vapor pressure over the drop, E_∞ is the saturation tension over the flat water surface, and a is a coefficient depending on a number of factors.

From experimental data, Bergeron obtained a $(1/2.3) \times 10^{-6}$. Taking this value and assigning values to ΔE, which equals $E_r - E_\infty$, we draw up Table 2.

Table 2. Final Drop Radius (r_2) for Various ΔE's for Time Intervals of 10, 100, and 1,000 Seconds

	ΔE (g/m^3)								
	0.1			0.01			0.005		
r_1 (microns)	t seconds								
	10	100	1000	10	100	1000	10	100	1000
0.1	6.5	20.7	65.6	2.1	6.6	20.7	1.5	4.6	14.7
1.0	6.6	20.8	65.6	2.3	6.6	20.8	1.8	4.7	14.7
10.0	12.0	23.0	66.3	10.2	12.0	23.0	10.2	11.0	17.7

Thus, for a temperature of about 10° and supersaturations of 1.5 to 2% (ΔE=0.1 g/cu m), drop radii which differ by a factor of 100 initially become equal after several minutes. Even for lower supersaturations which are closer to actual atmospheric conditions, small droplets which have just been created become equal to the larger drops after 10-20 minutes.

Therefore, it seems that the modal size of cloud drops is determined by the conditions of water vapor condensation and the time of operation of this process, i.e., is primarily some function f(ΔE, t). Secondary maxima of the distribution curve are explained naturally by coalescence processes, but not by the sizes of condensation nuclei. In connection with this, it is interesting to recall the drop-mass relations established by Kohler, which are usually cited in basic meteorological texts such as Obolenskiy's Kurs Meteorologii, A Course in Meteorology.)

The law of multiples was first noted for rain drops by Defant, who observed that the weight of drops was usually related as 1:2:3:4:6:8:12, etc. Later it was found that this series was composed of four groups of drops, namely:

I - 1: 2: 4: 8: 16:

II - 1: 3: 6: 12:

III - 1: 5: 10: 20:

IV - 1: 7: 14: 28:

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The same weight relationship was found by Kohler (H. Kohler, "Investigations of the Clements of Fogs and Clouds," Medd fran. Stat. Met. Hydr. Anstalt., No 2, 5, 1925) for cloud droplets; but as a result of more detailed processing, he was able to express the relationship between drop sizes as $r = B \cdot 2^{\frac{n}{3}}$, where $n = 1, 2, 3 \ldots\ldots$, r is the the drop radius, and B is the reference drop which had to be determined from experimental data. Later, Kohler further refined the formula to the form $r = B_1 2^{\frac{p}{3}} \cdot 2^{\frac{n}{3}}$ where p is an integer on which $B = B_1 2^{\frac{p}{3}}$ depends.

On the basis of the law of multiples, Kohler concluded that drops of equal size coalesce in pairs; this conclusion also was incorporated in meteorological literature.

Contemporary ideas on cloud processes do not agree with Kohler's law. Along with the fact that the probability of coalescence of drops of unequal size is high, condensation and evaporation processes also affect the size of drops. Nonetheless, there is some interest in calculating the recently obtained curves of drop-mass distribution. For this purpose, several cases were selected which had sharply defined secondary maxima on the ordinary distribution curve. Calculations showed that the maxima were sometimes quite close to multiple-mass values. For example, in two cases, the maximum drop weights were as follows: (1) 1.8, 5.2, 11.5, $25.7 \cdot 10^{-10}$; (2) 2.7, 5.2, 9.1, 14.6, 36.0, $48.4 \cdot 10^{-10}$

Thus, although these masses were not exact multiples, values of n, p, and B might be selected in a number of cases which would with the proper processing give values of r quite close to those expressed by the Kohler formula for certain intervals. In the numerous cases where the distribution curves have only one maximum, there is no hint of drop-mass multiples. It follows therefore than Kohler's law is not general for clouds and may have only limited application.

The distribution curves have the following characteristics with respect to cloud types: narrow unimodal curves (Figures 1 and 3) are characteristic of Cu and local St; unimodal curves with the maximum toward small drop sizes are also characteristic of As and Ac, but unlike the types first mentioned, the latter curves are frequently heavily right-skewed (Figure 2).

Ns is characterized by simple high-kurtosis curves with modes toward the larger drop sizes (about 20 microns) or by complex multimodal curves.

Interestingly enough, a distribution curve with two or more maxima is always obtained for St (or FrSt, since they cannot always be distinguished in the mountains) and Sc in combination with other clouds (usually with Ns Ac, or Cb). This was observed in the El'brus expedition (St - Group II) and in airplane tests. Nothing definite is known about what causes secondary maxima in these types, but apparently they are not caused by a drop falling from the upper layer of clouds. Diem pointed out that there is usually a considerable cloudless interval between the lower and upper cloud which is sufficiently dry to evaporate falling drops. These secondary maxima are apparently caused by the state of the medium and processes in the lower cloud layer. During observations on El'brus in 1940, the remark "The fog passes in waves which are nonuniform in density" was made in all cases of St - Group II. Other weather notes indicate that this was a case of bad weather with considerable gustiness; consequently, the growth of drops under these conditions might be due to turbulence.

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There are many references in literature to the Houghton curves mentioned previously. The maxima of these curves do not coincide with the maxima of the distribution curves but are displaced toward larger drop sizes. The maximum on the curve of relative volumes gives the drop size which determines the content of liquid water in the cloud and is a different characteristic from the ordina y modal or most frequent drop size. It is sometimes mistakenly stated that the mod l drop size in America is 40-50 microns (diameter), i.e., larger than ours and European data (for example, this remark is contained in the work by Diem). When our ordinary distribution curves are converted to relative volume curves, curves identical with Houghton's are obtained.

We would like to make several other clarifying remarks on the water content of clouds (amount of liquid water per unit volume) and the concentration of drops in them (number of drops per unit volume).

First, we point out that there have been few direct measurements of these quantities and that the methods used were not perfect. Ordinarily, these two values are determined together, i.e., one of them is measured and the other is calculated from the known distribution of drops or their average size.

The first evaluations of the number of drops per unit volume of clouds were undoubtedly high. Some figures ran as high as 1,000 drops/cc, and it was generally agreed that the number was at least 500 (e.g., see Obolenskiy's Kurs Meteorologii). These figures were high because high figures for water content were used in addition to some other factors. Illustrating these other factors, it was assumed that the number of drops should correspond to the number of condensation nuclei. It is well known however, that counters of condensation nuclei operating under considerable supersaturations will show more nuclei than those actively participating in condensation processes in the atmosphere. In addition, because of coalescence of drops, their number can often be considerably less than the number initially formed. Nevertheless, admitting the commensurability of these two quantities, we also attempted to represent the possible concentration of drops through the number of condensation nuclei in processing El'brus data. For this purpose, the average number of nuclei in clouds and in the absence of clouds was determined for the height, 4,250 m. Morning observations were used to exclude the effect of diurnal behavior. The number of nuclei in clouds proved to be 150-250 per cc less than during cloudless days. Taking into consideration the remarks above on coalescence of drops, a number of 200 per cc might be slightly high.

Houghton stated in one of his works that the number of drops in clouds and fogs varies from 50 to 500. These values were apparently obtained from water-content measurements. Similar calculations were made earlier from water-content measurements in the Alps. According to this data, an average liquid water content of 1-2 g/cu m must have been used, but this value is slightly high. The water content reaches several grams per cubic meter only for intensive condensation and high temperatures; most often, as later measurements showed, fractions of a gram of liquid water are contained in clouds in the free atmosphere (according to Diem, for example, the highest values were 0.4-0.6 g/cu m and the m dal value was approximately 0.2 g/cu m).

Finally, there is still one more error in calculations of the number of drops from water content, and that is that the modal size of the drop r obtained from optical measurements or from frequency curves is usually used. For accurate calculations, the entire spectrum of drops should be taken into consideration or the modal value from the Houghton curve should be taken. The use of the simple modal r also leads to high values for the number of drops.

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For water content of 0.2-0.3 g/cu m and average distribution of drops, the number of drops per unit volume should be around 100. Clouds with high water content (1-2 g/cu m) are characterized by higher modal values for drop sizes and by the presence of very large drops (with diameters of several score microns). The latter practically determine the water content; the number of drops in such clouds may be even less than in "small-drop" clouds. The only thing which might affect substantially the figure of 100 is ultra microscopic droplets ($d < 1$ micron). They do not have any noticeable effect on water content, but their number may sometimes be high.

As was mentioned previously, the water content of clouds can be found from the number of drops per unit volume and their distribution with respect to size. This method of evaluating the amount of liquid water is suggested because up to this time the methods used for direct measurements of the amount of liquid water in clouds are inaccurate and it is easier to determine the concentration of drops.

It is evident that the water content of clouds, given the same number of drops, depends strongly on their distribution, as illustrated by the following example: the water content W is 0.12 g/cu m in St, assuming 100 drops/cc and simple form of distribution curves (group I in the processed El'brus data), whereas it is 0 29 g/cu m for the same clouds for another distribution (Group II, Figure 3). These values also show that in clouds with similar drop distribution (in St, Sc, Ac, Cu), the water content is not over 1 g/cu m even for a considerable number of drops e.g., 200 to 300 drops/cc.

Conclusions

Clarification of the microstructure of cloud types is of great practical interest. Structural differences of different clouds are natural since the morphological characteristics reflect the state of the atmosphere. Bergeron apparently tried to create a physicogenetic classification of clouds on this basis. Observational results did not produce a clear picture, however, and Bergeron's classification was not confirmed. The structural characteristics apparently do not depend uniquely on the macroprocesses which determine the external appearance of clouds.

We could also assume that the microstructure of clouds depends on the physical characteristics of the atmosphere, i.e., temperature T, and relative f, absolute e, or specific q humidity. Naturally, q_{max} is low for low temperatures, and this must affect cloud water content and consequently the size of drops (for the same number of condensation nuclei). Actually, there are indications in works on aircraft icing that supercooled drops are very small at low temperatures; this is reflected in the form and light intensity of icing.

Bricard compared drop size with temperature and humidity, but did not obtain any definite results. More accurately, he concluded that no relationship exists for positive temperatures; he did not investigate the relationship under negative temperatures. It is also difficult to draw any conclusions from the El'brus observations in view of the slight temperature fluctuations (from $+2$ to $-4°$). The temperature amplitudes were greater in Diem's airplane flights, but even here no dependence of structural characteristics on temperature was found. Of course, it is possible that for large temperature amplitudes the difference in moisture content affects the cloud water content. In general, however, the dependence of cloud microstructure on temperature and humidity cannot be simple and direct. The intensity of the condensation process and the water content of the cloud thus formed is determined by the supply of water vapor and the value of ΔE ($= E_r - E_\infty$) created.

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For a given supply of water vapor, there must be some most probable drop size d_m which varies very slowly with time; coalescence processes cause considerable growth of the drops in comparison with d_m and especially growth to the size of drizzle and rain.

Thus, we must search for a dependence of cloud microstructure on the water vapor supply, and not on the absolute values of T and q. The problem of determining the supply of water vapor is in itself quite complex, but it can be solved for some partial cases. For example, for radiation fogs, Kiryukhin (B. V. Kiryukhin, "The Intensity and Duration of Radiation Fogs," Trudy NIU GUGMS SSSR, Series 1, No 28, 1946) determined water content from the drop in temperature below the dew point, considering the total moisture content constant throughout the existence of the fog. Kropotov (Ye. Kropotov, "Turbulent Transfer of Water Vapor Through Inversion Layers and the Icing Conditions of Aircraft in These Layers Connected With It," Izvestiya Voyenno-Morskoy imeni Voroshilov Akademii, No 7, 1941) gave a method for calculating the supply of water vapor near inversion layers. The latter processed many sounding observation on icing, but unfortunately these observations did not include any data on cloud microstructure, and thus this material cannot be used.

Future studies on cloud microstructure should be organized so that real values for the supply of water vapor and the quantity ΔE can be obtained along with drop sizes. Measurements at different heights in the same cloud are also important.

According to the distribution curves of drops, it is apparent that their size (diameter) is no greater than 40-50 microns, while the modal values d_m vary from 5 to 20 microns. This is confirmation of the fact that there are no important supersaturations in clouds, as is sometimes assumed. Even at supersaturations of 1-2%, the condensation process, as shown in Table 2, would provide a rapid growth of all drops to a size greatly exceeding the average size of cloud drops. Judging from the stability of the modal values, we can assume only slight supersaturation relative to the drops.

/Appended figures follow./

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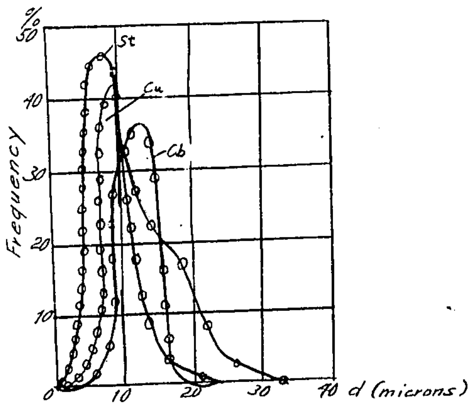

Figure 1 Distribution of Drops in Clouds (from El'brus Data)

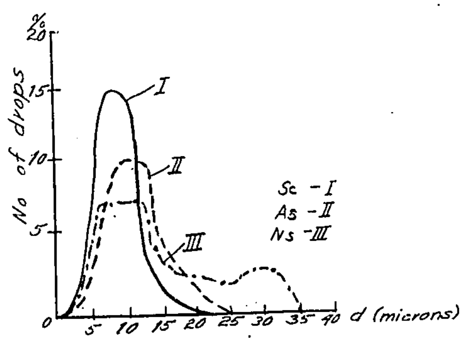

Figure 2. Distribution of Cloud Drops

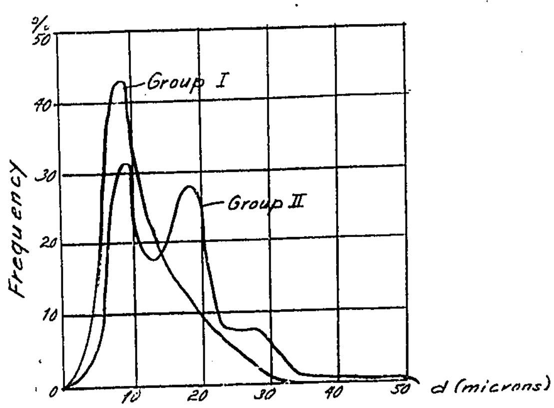

Figure 3. Distribution of Drops in St's of Different Origin (El'brus)

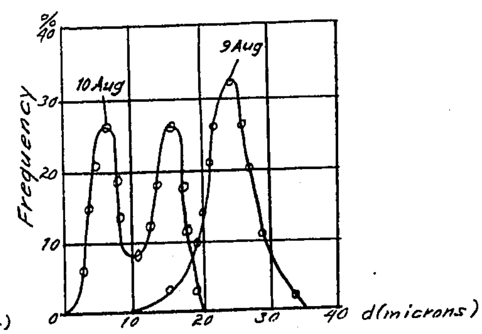

Figure 4. Two Cases of Drop Distribution in Ns (El'brus)

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